Calibration Method and Measurement Uncertainty for the Sphere Center Distance of Standard Multi-ball Bar

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Abstract. A calibration method for the sphere center distance of standard multi-ball bar was proposed. According to the calibration method, the evaluation model of measurement uncertainty was established, and the sources of uncertainty were analyzed. The expanded uncertainty is less than one third of the nominal error, which verifies the feasibility and effectiveness of the calibration method

Keywords: Metrology; Standard multi-ball bar; Coordinate Measuring Machine; Uncertainty in measurement.

1. Introduction

The standard ball bar is composed of two (or more) spheres and the ball bar connecting the spheres. It is a standard instrument used for the calibration of three-dimensional coordinate measurement system. Common 3D coordinate measurement systems include 3D laser scanners (SAMR, 2021), which are commonly used for surface measurement of large curved surfaces, such as automobile body sheet metal processing detection (Gao-yu, 2021). The balls of standard ball bar are usually made of steel, hard alloy, ceramics and other materials. The ball surface can be polished or diffuse. Ball clubs are usually made of carbon fiber with small linear expansion coefficient characteristics. In order to calibrate the standard ball bar, reference (Liu-Fangfang, 2018) constructed a sphere distance of ball bar measuring device based on the principle of laser interferometry, and analyzed its measurement uncertainty. In literature [Huang-kun, 2019], based on the principle of laser interferometry, the author developed a new sphere distance of ball bar calibration instrument by using a triangle indirect measurement method of ball pitch. The above method is applicable to two ball clubs, while multi-ball bars cannot be measured. In JJF1859-2020 calibration specification for standard ball bar (SAMR, 2020), the main metrological characteristics of standard ball rods include ball diameter, sphere shape error, sphere center distance, etc. This calibration specification recommends the use of coordinate measuring machines to calibrate standard ball bars. According to the requirements of JJF1859, this paper uses coordinate measuring machine to measure the sphere center of standard multi-ball bar, and evaluates the measurement uncertainty.

2. Calibration method

Fix the standard ball bar on the CMM workbench. Select 25 measuring points on the sphere surface of the ball to obtain the coordinate point set of the sphere surface. The arrangement method of 25 measuring points is as follows: 1 point is at the pole position of the standard sphere, 4 points are evenly distributed at 22.5° below the pole, 8 points are evenly distributed at 45° below the pole and 22.5° relative to the top group of 4 points, 4 points are evenly distributed at 67.5° below the pole and 22.5° relative to the top group of the 8 points, and 8 points are evenly distributed at 90° below the pole and 22.5° relative to the top group of 4 points. The location of measuring points is shown in Figure 1.

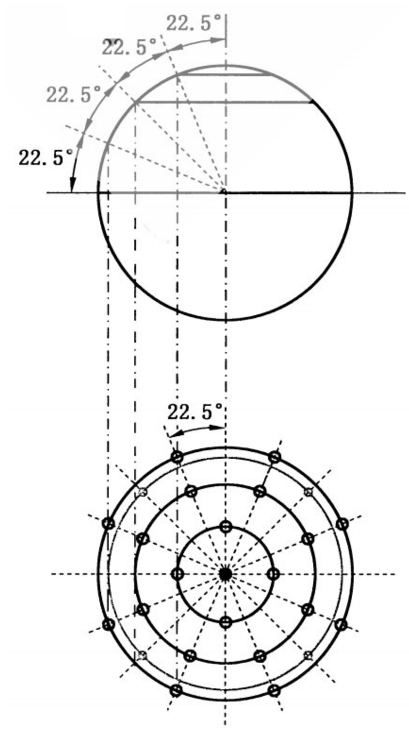

Fig. 1. Schematic diagram of the measuring points coordinates on Sphere Surface

Use the CMM to measure the 25 points of each ball to obtain a set of coordinate points. The shape of the ball is obtained by least square fitting, and the sphere center coordinates (x_i, y_i, z_i) of the ball to be measured are obtained. Using the same method, the sphere center coordinates of other balls on the standard ball bar are obtained. Then the sphere center moment L_{ij} of standard ball i and ball j can be calculated as follows

$$L_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{1}$$

where L is the measured sphere center distance of the balls being calibrated, x_i, y_i, z_i are the measured sphere center coordinates of ball i, x_j, y_j, z_j are the measured sphere center coordinates of ball j.

3. Evaluation of measurement uncertainty

3.1 Measurement model

See Formula (1) for the measurement model of sphere center distance of standard multi-ball bar. Because each component is independent of each other, the combined standard uncertainty is calculated by the following formulas

$$\begin{gathered} u^2(L) = c_1^2 u^2(x_i) + c_2^2 u^2(x_j) + c_3^2 u^2(y_i) + \\ c_4^2 u^2(y_i) + c_5^2 u^2(z_i) + c_6^2 u^2(z_j) \end{gathered} \tag{2}$$

$$c_1 = \frac{\partial L}{\partial x_i} = \frac{x_i - x_j}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{3}$$

$$c_2 = \frac{\partial L}{\partial x_j} = \frac{x_j - x_i}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{4}$$

$$c_3 = \frac{\partial L}{\partial y_i} = \frac{y_i - y_j}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{5}$$

$$c_4 = \frac{\partial L}{\partial y_j} = \frac{y_j - y_i}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{6}$$

$$c_5 = \frac{\partial L}{\partial z_i} = \frac{z_i - z_j}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{7}$$

$$c_6 = \frac{\partial L}{\partial z_j} = \frac{z_j - z_i}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}} \tag{8}$$

3.2 Calculation of standard uncertainty

3.2.1 Calculation of $u(L_0)$

Standard uncertainty component $u(L_0)$ is introduced by repeatability of sphere coordinate measurement. According to the measurement method in 6.1 of JJF1859-2020(SAMR, 2020), use the coordinate measuring machine to repeatedly measure the standard ball rod for 10 times, and take the average of the sphere center coordinates measured for 10 times as the sphere center coordinates, as shown in Table 1.

Table 1. Measured value of the baseball center coordinate of the measured standard ball. unit: mm

No. of ball	x_i	y_i	z_i
1#	-0.00008	-0.00012	0.00002
2#	-0.00026	241.60073	64.33002
3#	-0.03696	966.38600	257.18103
4#	-0.07151	1430.24013	380.65560

The sensitivity coefficient of each sphere center distance is calculated according to the measured values of sphere center coordinates in Table 1. The settlement results are shown in Table 2.

Table 2. Results of sensitivity coefficient of uncertainty of sphere center distance.

No. of two balls	c_1	c_2	c_3	c_4	c_5	c_6
1#-2#	0.000	0.000	-0.966	0.966	-0.257	0.257
3#-4#	0.000	0.000	-0.966	0.966	-0.257	0.257
2#-3#	0.000	0.000	-0.966	0.966	-0.257	0.257
1#-3#	0.000	0.000	-0.966	0.966	-0.257	0.257
2#-4#	0.000	0.000	-0.966	0.966	-0.257	0.257
1#-4#	0.000	0.000	-0.966	0.966	-0.257	0.257

Take the standard deviation of x_1, y_1, z_1, x_2, y_2, z_2, corresponding to each sphere distance measured repeatedly for 10 times as the uncertainty component, and calculate the standard uncertainty component $u_i(L_0)$ introduced by the repeatability of sphere coordinate measurement in each sphere distance measurement. The calculation results are shown in Table 3. Take the maximum value as the standard uncertainty component u (L_0).

Table 3. Results of standard uncertainty component $u(L_0)$.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
$u_i(L_0)$ (μm)	0.19	0.23	0.25	0.13	0.19	0.22

3.2.2 Calculation of $u(L_c)$

The standard uncertainty component $u(L_c)$ is introduced by CMM spatial dimension measurement error. MPE measured according to CMM space dimension is ± (0.4μm+1.2×$10^{-6}L$), assuming uniform distribution, the calculation results of the standard uncertainty component $u(L_c)$ introduced by the CMM space dimension measurement error in the measurement of sphere center distance are shown in Table 4.

Table 4. Standard uncertainty component introduced by CMM spatial dimension measurement error $u(L_c)$.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
MPE (μm)	±0.70	±0.98	±1.30	±1.60	±1.85	±2.14
$u(L_c)$ (μm)	0.40	0.56	0.74	0.91	1.07	1.24

3.2.3 Calculation of $u(L_a)$

The standard uncertainty component $u(L_a)$ is introduced by the influence of temperature change on the ball bar during measurement. The expansion coefficient of ball bar carbon fiber rod is -2.0×10^{-6}℃, the temperature change during the measurement is less than ±0.1℃, assuming uniform distribution in the area, Class B method is used for evaluation. The standard uncertainty component $u(L_a)$ introduced by the temperature change during the measurement of each sphere center distance is shown in Table 5.

Table 5. The standard uncertainty component introduced by the influence of temperature change on the ball bar during measurement $u(L_a)$.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
$u(L_a)$ (μm)	0.03	0.06	0.09	0.12	0.14	0.17

3.2.4 Calculation of $u(L_b)$

The standard uncertainty component $u(L_b)$ is introduced by difference of linear expansion coefficient of temperature between calibrated ball bar and CMM grating ruler. The expansion coefficient of carbon fiber rod of the ball bar to be calibrated is -2.0×10^{-6}℃, the range of ambient temperature change is less than ±0.2℃, and the expansion coefficient of glass grating ruler of CMM is 0.1×10^{-6}℃, assuming that it is uniformly distributed in the area, Class B method is adopted for evaluation.

When measuring the sphere center distance, the ambient temperature changes, and the linear expansion coefficient of the temperature of the calibrated ball stick and the coordinate measuring machine grating ruler is different. The calculation results of the standard uncertainty component $u(L_b)$ introduced are shown in Table 6.

Table 6. Standard uncertainty component introduced by different linear expansion coefficients $u(L_b)$.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
$u(L_b)$ (μm)	0.06	0.12	0.18	0.24	0.30	0.36

3.3 Combined standard uncertainty

Since the components of each standard uncertainty are not related to each other, the combined standard uncertainty is calculated according to Formula (9). The results of the combined standard uncertainty of each sphere center distance measurement are shown in Table 7.

$$u_c = \sqrt{u^2(L_o) + u^2(L_c) + u^2(L_a) + u^2(L_b)} \tag{9}$$

Table 7. Composite standard uncertainty of each sphere distance measurement.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
u_c (μm)	0.48	0.63	0.81	0.98	1.15	1.33

3.4 Expanded uncertainty

Taking the coverage factor k=2, the calculation results of the expanded uncertainty of the calibration of each sphere center distance of the standard multi-ball bar are shown in Table 8.

Table 8. Expanded uncertainty of each sphere distance measurement.

No. of two balls	1#-2#	3#-4#	2#-3#	1#-3#	2#-4#	1#-4#
nominal value (mm)	250	480	750	1000	1230	1480
U (k=2)	0.96	1.26	1.62	1.96	2.30	2.66

Linearize the nominal value of sphere center distance in Table 8 and its corresponding expanded uncertainty, and the expanded uncertainty $U(k=2)$ of standard multi-ball sphere center distance is, where L is the nominal length of ball center distance

$$U = 0.6\mu\text{m} + 1.5\times10^{-6} L \tag{10}$$

4. Conclusions

According to the calibration method, the evaluation model of measurement uncertainty was established, and the sources of uncertainty were analyzed. The expanded uncertainty is less than one third of the nominal error, which verifies the feasibility and effectiveness of the calibration method.

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